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EXAMINER	
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2813	

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Please find below and/or attached an Office communication concerning this application or proceeding.

Advisory Action	Application No. 09/634,556	Applicant(s) CHANG ET AL.	
	Examiner Thanhha Pham	Art Unit 2813	

--The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

THE REPLY FILED 2/28/03 FAILS TO PLACE THIS APPLICATION IN CONDITION FOR ALLOWANCE. Therefore, further action by the applicant is required to avoid abandonment of this application. A proper reply to a final rejection under 37 CFR 1.113 may only be either: (1) a timely filed amendment which places the application in condition for allowance; (2) a timely filed Notice of Appeal (with appeal fee); or (3) a timely filed Request for Continued Examination (RCE) in compliance with 37 CFR 1.114.

PERIOD FOR REPLY [check either a) or b)]

a) ☒ The period for reply expires 3 months from the mailing date of the final rejection.

b) ☐ The period for reply expires on: (1) the mailing date of this Advisory Action, or (2) the date set forth in the final rejection, whichever is later. In no event, however, will the statutory period for reply expire later than SIX MONTHS from the mailing date of the final rejection.
ONLY CHECK THIS BOX WHEN THE FIRST REPLY WAS FILED WITHIN TWO MONTHS OF THE FINAL REJECTION. See MPEP 706.07(f).

Extensions of time may be obtained under 37 CFR 1.136(a). The date on which the petition under 37 CFR 1.136(a) and the appropriate extension fee have been filed is the date for purposes of determining the period of extension and the corresponding amount of the fee. The appropriate extension fee under 37 CFR 1.17(a) is calculated from: (1) the expiration date of the shortened statutory period for reply originally set in the final Office action; or (2) as set forth in (b) above, if checked. Any reply received by the Office later than three months after the mailing date of the final rejection, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

1.☐ A Notice of Appeal was filed on _____. Appellant's Brief must be filed within the period set forth in 37 CFR 1.192(a), or any extension thereof (37 CFR 1.191(d)), to avoid dismissal of the appeal.

2.☐ The proposed amendment(s) will not be entered because:

(a) ☐ they raise new issues that would require further consideration and/or search (see NOTE below);

(b) ☐ they raise the issue of new matter (see Note below);

(c) ☐ they are not deemed to place the application in better form for appeal by materially reducing or simplifying the issues for appeal; and/or

(d) ☐ they present additional claims without canceling a corresponding number of finally rejected claims.

NOTE: _____.

3.☐ Applicant's reply has overcome the following rejection(s): _____.

4.☐ Newly proposed or amended claim(s) _____ would be allowable if submitted in a separate, timely filed amendment canceling the non-allowable claim(s).

5.☒ The a)☐ affidavit, b)☐ exhibit, or c)☒ request for reconsideration has been considered but does NOT place the application in condition for allowance because: See Continuation Sheet.

6.☐ The affidavit or exhibit will NOT be considered because it is not directed SOLELY to issues which were newly raised by the Examiner in the final rejection.

7.☒ For purposes of Appeal, the proposed amendment(s) a)☐ will not be entered or b)☐ will be entered and an explanation of how the new or amended claims would be rejected is provided below or appended.

The status of the claim(s) is (or will be) as follows:

Claim(s) allowed: none

Claim(s) objected to: none

Claim(s) rejected: 1-16.

Claim(s) withdrawn from consideration: 17-24.

8.☐ The proposed drawing correction filed on _____ is a)☐ approved or b)☐ disapproved by the Examiner.

9.☐ Note the attached Information Disclosure Statement(s)(PTO-1449) Paper No(s). _____

10.☐ Other: _____

Carl Whitehead
CARL WHITEHEAD, JR.
SUPERVISORY PATENT EXAMINER
TECHNOLOGY CENTER 2800

Continuation of 5. does NOT place the application in condition for allowance because: APA discloses printing a plurality of bumps of an insulating material by photolithography technique -- photolithography technique is one of printing technique in fabrication technology of semiconductors (see Jackson et al, :"Handbook of seniconductor technology", vol 2, pp 182-192 in attachment). .

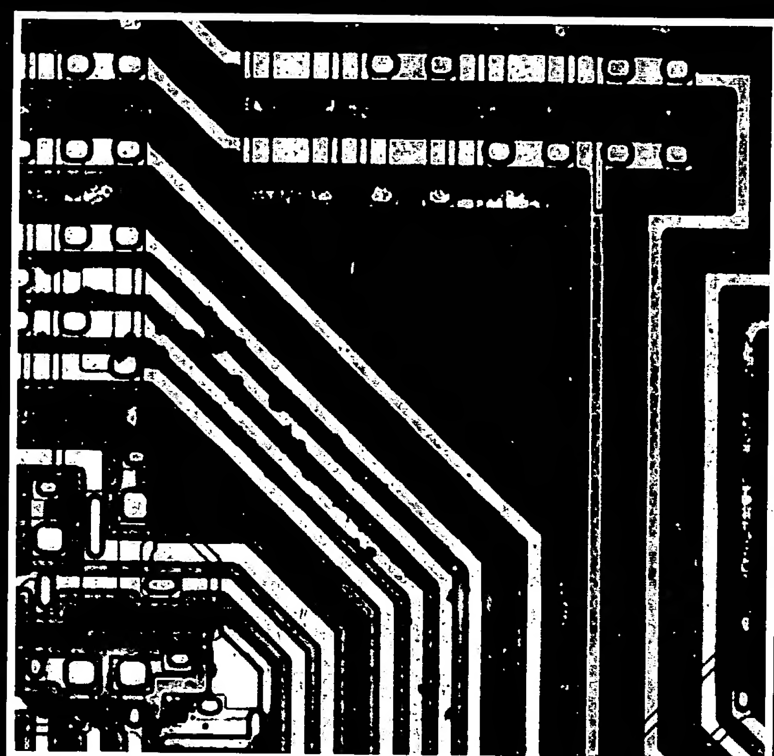
WILEY-VCH

Handbook of Semiconductor Technology

Processing of Semiconductors

Edited by K. A. Jackson and W. Schröter

Volume 2



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4 Photolithography

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List of Symbols and A

CD	critical dime
DR	dissolution r
DOF	depth of foc
D_p^0, D_n^0	dose to clea
E_a	activation er
FT	film thickne
G	proximity g
k_1, k_2	constants
n	refractive in
NA	numerical a
$O.N.$	Ohnishi nun
r	ring parame
R	reflectivity
S	swing ratio
T_G	glass transit
α	resist absor
γ	resist contra
ε	extinction c
θ	angle
γ	wavelength
AAS	atomic abso
ABC	(azidobenza
AFM	atomic forc
AHR	acid-harden
ALC	acid labile
APSQ	acetylated p
ARC	antireflecti
ARCH	advanced re
ASIC	application
BARC	bottom anti
BCB	benzocyclo
BDMADS	bis(dimeth
CA	chemical a
CAR	chemical a
CARL	chemical a
CEL	contrast en
CMP	chemical-m
CoO	cost of owr
CQUEST	Canon qua
DESIRE	diffusion e
DNQ	diazo-naph

4.1 Introduction

The definition of the numerous electrical functions assembled on integrated circuits (ICs) is usually accomplished with the aid of an illumination-based imaging technique called photolithography. Photolithography provides a method to transform a complex master image with radiation into thousands of three-dimensional replicas of a photoresist film coated onto a substrate with utmost accuracy, speed and cost efficiency. The real or digitized master image is provided by either a mask or a serial writing technique. Being stroked by the radiation, the exposed photoresist areas change their solubility or polarity properties. The material's chemistry selection and its processing conditions determine the tonality of the relief image: If the reproduction corresponds to the original, it is termed a positive; if it is reversed, it is a negative reproduction. The discrimination between image and nonimage areas is accomplished by selective removal of either the exposed (positive) or unexposed (negative) resist through a development method (Fig. 4-1), resulting in the desired three-dimensional relief image. The remaining photoresist portions protect the underlying substrate from the attack of processing chemicals, e.g., etching agents, and allow the whole device to be subjected to the undifferentiated action of these.

Photolithography has become an inevitable element in the manufacturing sequence of microelectronic circuits and other devices, such as multi-chip modules (MCMs) (Lall and Bhagath, 1993), micromechanical devices (Rogner et al., 1992), thin film recording heads for magnetic disks (Bond, 1993), color filters (Kudo et al., 1996a, b), or thin film transistor/liquid-crystal displays (TFT/LCD) (Howard, 1992; Bardsley, 1998). Many of these products are integral parts of the hardware platform mandatory for an effective handling of the growing information density worldwide.

The base material for the production of an integrated circuit consists of an intensively cleaned, highly polished disk, called a wafer, with a diameter up to 300 mm (Brunkhorst and Sloat, 1998; Bullis and O'Mara, 1993), which has been sliced from a large monocrystalline silicon rod of extreme purity. Each wafer provides hundreds of small separate chips, containing millions of electrical elements, such as capacitors, diodes, and transistors on a field size of 1 to $2\,cm^2$. During its metamorphosis from a polished silicon plate to disk carrying ICs, the wafer is subjected to many different operations. Certain key steps are used repeatedly in IC fabrication, among which lithography plays a dominant role to delineate the patterns of conducting and insulating areas (Einspruch, 1985).

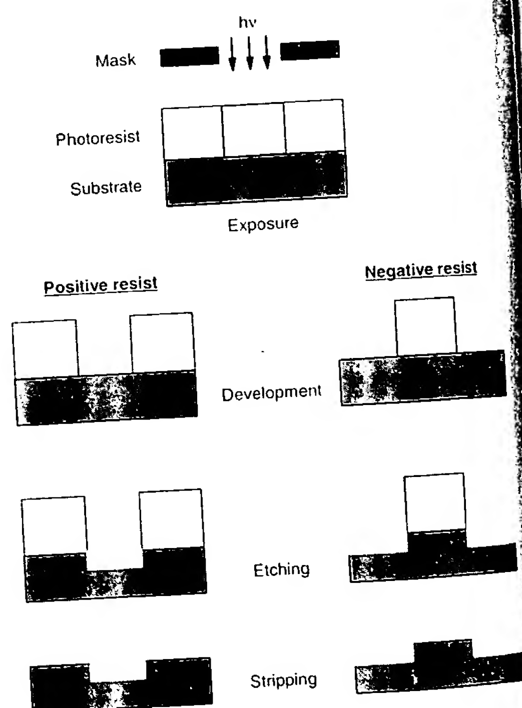

Figure 4-1. Formation of positive and negative tone pattern.

Initially, the wafer is thermally oxidized at ~1000 °C. During this step a thin layer of silicon dioxide grows on the silicon substrate. This SiO_2-layer will protect selected areas of the substrate from penetration by dopant ions. The wafer is spin-coated with a solution of the photoresist, which solidifies to a uniform 0.5 to 2 mm thick film after the solvent is evaporated on a hot-plate at elevated temperature. The coated wafer is then imagewise irradiated and the soluble resist portions are removed by a development procedure. Next, the SiO_2-layer, which is imagewise protected by the resist, is etched away where it is uncovered to open the desired portions of the silicon surface. At this point, the resist is removed (stripped) to avoid device contamination with resist impurities.

The wafer is now ready for a further key processing step: ion implantation, which gives the silicon its electrical properties. High-energy ions of dopant elements (boron, phosphorus) are fired at the wafer and penetrate the open areas of the silicon surface. The substrate surface is reoxidized, and the wafer is again coated with a photoresist to allow further processing, e.g. insulation, or metallization steps. In a final lithographic step, contacts and connections for pins used to plug the chip into a printed circuit board are defined. At present, up to 24 lithographic and more than 250 separate processing steps are employed for the manufacture of electronic devices, resulting in a production time of one month for a single chip (Bullis and O'Mara, 1993). A simplified IC manufacturing procedure is given in Fig. 4-2.

An ongoing challenge in IC production is to further shrink the lateral device geometry, with the aim of building even more complex circuits, e.g. dynamic random access memory (DRAM) devices with higher storage capacity. This demand for higher resolution is the driving force for steady improvement of the photolithographic process (Gargini et al., 1998). Figure 4-3 illustrates the developments of storage capacity and required feature size for memory devices (left), and summarizes the applied or required technologies and photoresist characteristics to produce the devices (right).

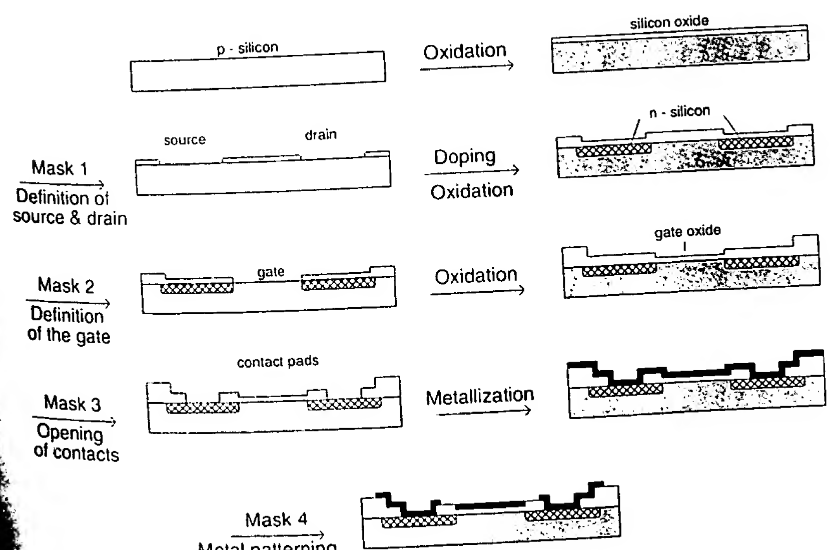

Figure 4-2. Planar technology: simplified production steps in MOSFET manufacture.

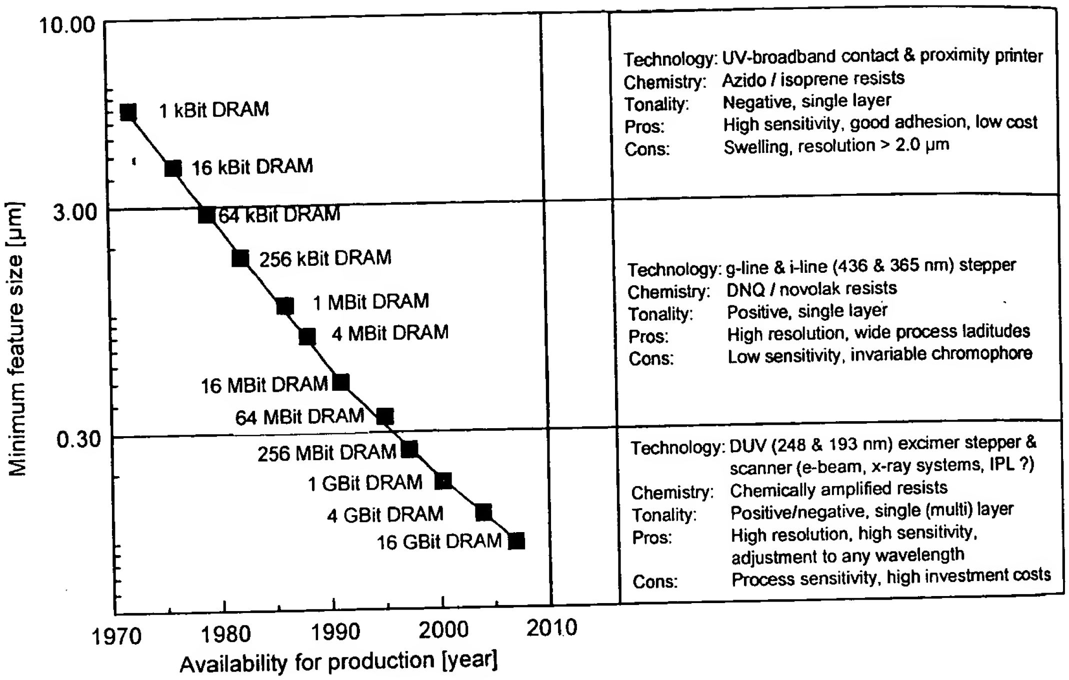

Figure 4-3. Development of storage capacity and minimum feature size of memory devices (left) and technologies usable for memory device production.

4.2 Exposure Tools

4.2.1 Image Formation and Resolution

ICs are usually patterned with near UV radiation sources, e.g. mercury/rare gas discharge lamps. To achieve optimum resolution, the emitted light is filtered and corrected by filter and lens systems to yield narrow-banded radiation. Contact, proximity or projection exposure tools (Fig. 4-4) have found commercial use, each having certain advantages, and handicaps over the other (Soane and Martynenko, 1989). The history of the different lithographic exposure tools is outlined by Bruning (1997).

In an optical lithographical system, light passes through the transparent areas of the mask. In the photoresist, the basic phenomenon to be seen is Fresnel diffraction. Figure 4-5 compares the aerial images of the above-described exposure methods. Contact printing readily approaches a perfect pattern transfer. But, with growing distance between mask and wafer (proximity printing), interference patterns occur, ending in an aerial image with a smooth distribution of the light intensity with its peak in the centre of the slit and tails beyond the area defined by the mask. When adjacent slits are projected, the situation becomes more complex, as a series of undulating maxima and minima are observed, with maxima smaller than 100% and minima greater than 0% transmission. The minimal printable linewidth CD (critical dimension) is given by the wavelength λ, the proximity gap G and the resist film thickness FT [Thompson et al., 1983; Eq. (4-1)]:

$$CD = 3/2\ \sqrt{\lambda(G + FT/2)} \tag{4-1}$$

In projection printing the special frequencies of the diffraction pattern are collected

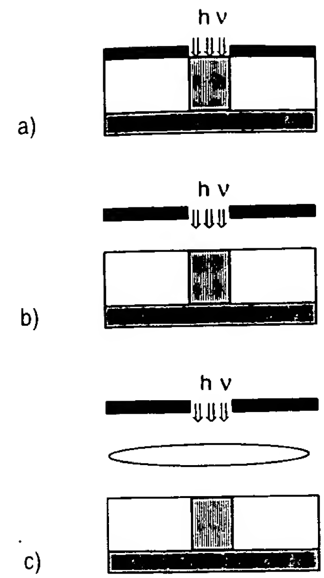

Figure 4-4. Mask/die arrangemei
proximity and (c) projection print

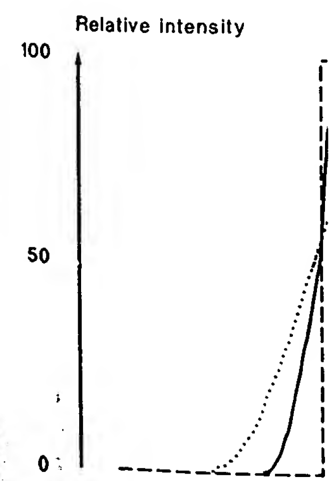

Figure 4-5. Comparison of aeri
after Soane, 1989.)

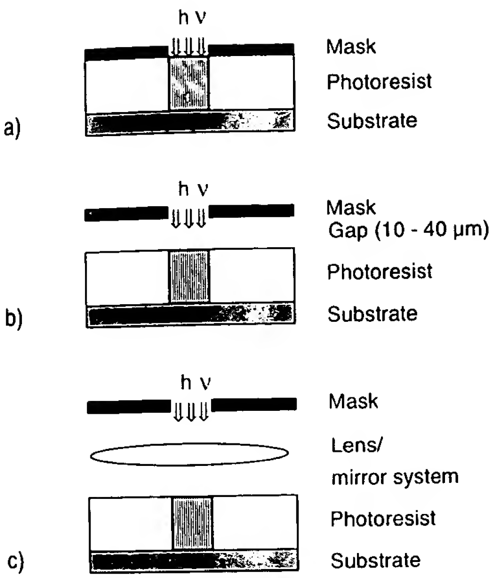

Figure 4-4. Mask/die arrangement in (a) contact, (b) proximity and (c) projection printing.

by the objective lens, which rebuilds the areal image of the mask in the wafer plane. For an ideal lens, the image quality is only restricted by the diffracted light that it does not pass through the lens due to the limited size of the numerical aperture (NA). The NA of a lens system in air is defined in Eq. (4-2), with θ denoting the maximum angle of the diffracted light that can enter the lens (Mack, 1993a):

$$NA = \sin(\theta/2) \tag{4-2}$$

A rough estimation of the limits of projection printing can be given by the Rayleigh [Eq. (4-3)]. The resolution (= critical dimension, CD) is a function of the radiation wavelength λ, the NA and an empirically determined constant k_1, which is governed by the type of photoresist, substrate, and the

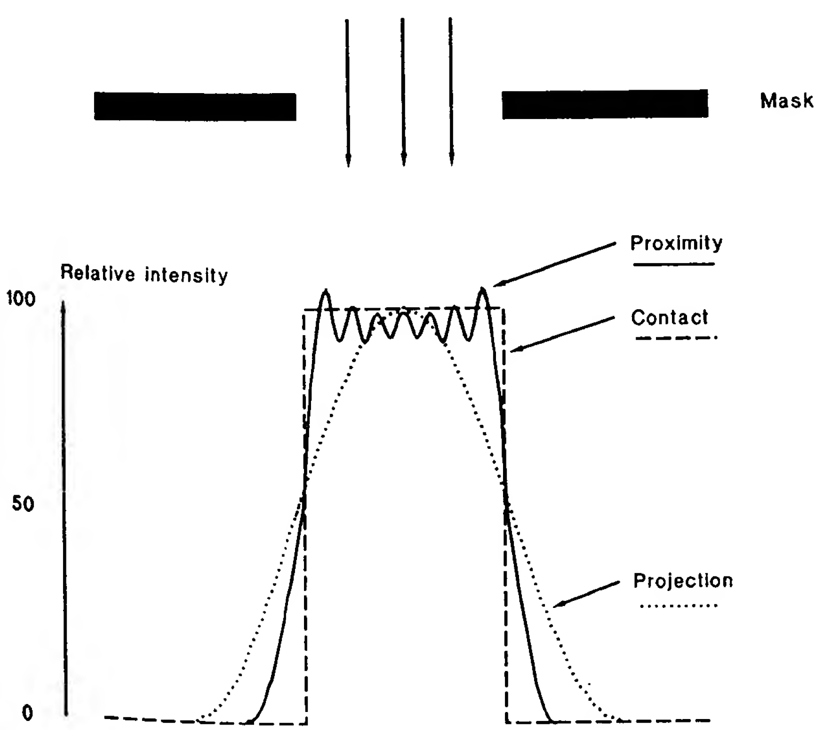

Figure 4-5. Comparison of aerial images obtained by contact, proximity and projection printing. (Reproduced after Soane, 1989.)

process environment (Lin, 1990). Under laboratory conditions, k_1 is assumed to be ≥ 0.5, whereas under production conditions, k_1 typically has a value of >0.8 to >1.2 depending on the reflectivity of the substrate.

$$CD = k_1 \cdot \lambda / NA \tag{4-3}$$

At a fixed wavelength, a larger *NA* allows the reproduction of smaller patterns. As seen from inspection of Eq. (4-4), the penalty for obtaining higher resolution by increasing the *NA* is a smaller depth-of-focus (*DOF*). The empirical constant k_2 in Eq. (4-4) also depends on the type of materials used.

$$DOF = k_2 \cdot \lambda / (NA)^2 \tag{4-4}$$

Values for k_2 are in the range of 0.4 to 0.9 under laboratory and production conditions. Studies by Dammel et al. (1990) and Boettiger et al. (1994) revealed that Eq. (4-4) is only roughly valid in the sub-half-micron range, and larger focus budgets than predicted may be observed in reality. From Eq. (4-3) it is obvious that a decrease of λ also will result in improved resolution capability, which thus may be obtained by either using NUV radiation with a high *NA* system, or by deep UV radiation with a smaller *NA*. A shorter wavelength λ should yield a better focus budget at a defined resolution but with shrinking feature size it cannot totally compensate the corresponding *DOF* reduction as shown in Fig. 4-6 (Arden, 1990). The *DOF* problem is a major physical limitation for single layer resists in optical submicron lithography, as a minimum resist thickness of >0.35 µm is necessary to ensure both coverage of the topography and sufficient etch resistance.

The considerations mentioned above are based on the assumption that the light strikes the mask only from one direction (coherent illumination). In reality, it comes from a

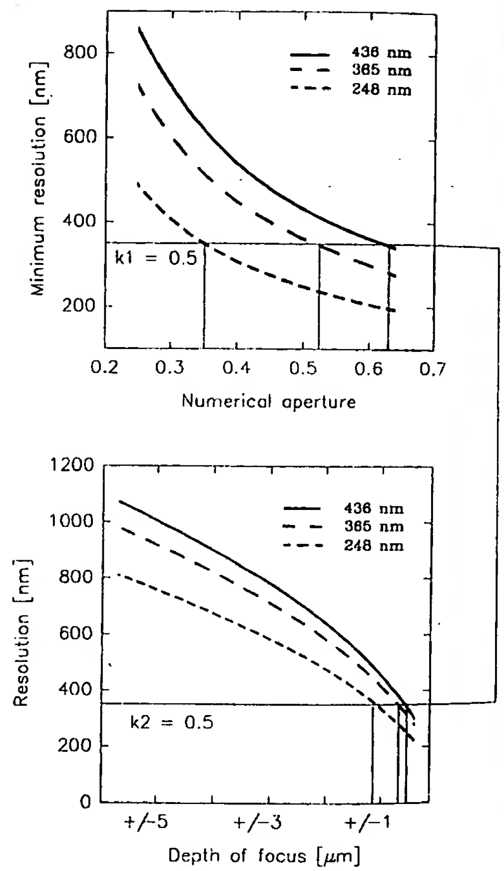

Figure 4-6. The impact of resolution on depth of focus.

range of angles rather than just one (partial coherence). The impact on the resolution is expressed by the modulation transfer function (MTF), which describes the image contrast as a function of the spatial frequency (Thompson et al., 1983 and Mack, 1993 A).

4.2.2 Contact and Proximity Printing

4.2.2.1 Optical Mask Aligner

With respect to the equipment, 1:1 contact printing is the simplest method. It is widely used for the production of devices with low resolution requirements (>5 µm). A mask consisting of a glass or quartz substrate carrying an array of thin chrome pat-

terns as absorber, is brought i
contact with the resist. This al
multaneous formation of many
one exposure, is cheap, and of
pattern reproduction. Repeated
tween mask and film may give r
scratches, or sticking of resist p
mask. Damaged mask patterns
produced in the resist, which r
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ing, and diminish the yield. In sl
imity exposure, the mask is se
gap of about 40 µm from the
This avoids contamination
problems, but causes degradati
tion due to diffraction effects (
(4-1)).

Optical mask aligners are usu
with mercury/xenon discharge
viding high output around: 40C
and 250 nm (Fig. 4-7). In c
ing, broad band illumination
because standing wave effe
pronounced when polychrom
used. Contact printing can
geously used to pattern very
layers (<200 µm) with high

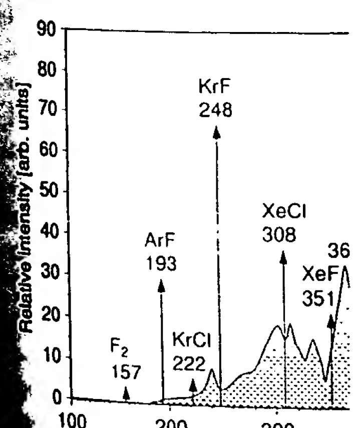

Figure 4-7. Comparison of emission
gies provided by a mercury lamp an
(Courtesy of W. Spiess. Reproduced

terns as absorber, is brought into intimate contact with the resist. This allows the simultaneous formation of many dies within one exposure, is cheap, and offers optimal pattern reproduction. Repeated contacts between mask and film may give rise to severe scratches, or sticking of resist pieces on the mask. Damaged mask patterns are then reproduced in the resist, which require additional time for reworking and mask cleaning, and diminish the yield. In shadow proximity exposure, the mask is separated by a gap of about 40 μm from the wafer plane. This avoids contamination and damage problems, but causes degradation of resolution due to diffraction effects (compare Eq. (4-1)).

Optical mask aligners are usually equipped with mercury/xenon discharge lamps providing high output around: 400 nm, 310 nm and 250 nm (Fig. 4-7). In contact printing, broad band illumination is preferred, because standing wave effects are less pronounced when polychromatic light is used. Contact printing can be advantageously used to pattern very thick resist layers (<200 μm) with high aspect ratios

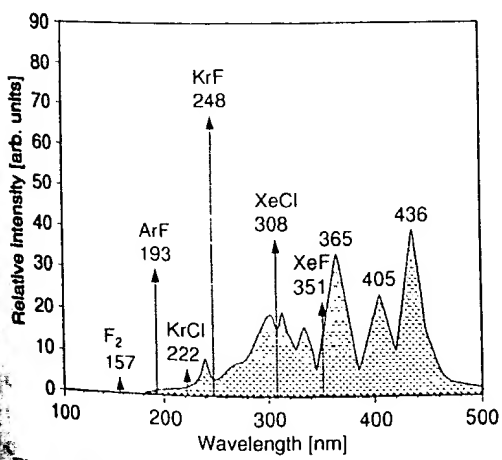

Figure 4-7. Comparison of emission spectra and energies provided by a mercury lamp and excimer lasers. (Courtesy of W. Spiess. Reproduced with permission.)

because the resist thickness is not limited by the depth-of-focus of any optical projection system (Loechel et al., 1994). Specially designed mask aligners allow for front and rear alignment (Cromer, 1993), which is needed for micromechanical applications, where the silicon substrate is etched through.

4.2.2.2 *X-Ray Stepper*

The resolution limits of optical systems using short wavelength radiation and improved resists together with optical tricks (Chu et al., 1991) are expected to be around 0.10–0.13 μm mainly due to the inadequate depth-of-focus budgets. Surface imaging schemes may give rise to further reductions of the device geometry at the price of increased process complexity. Ultra large scale integration (ULSI) patterns smaller than 0.13 μm without any depth-of-focus problem may be achieved using X-ray radiation (Peters and Frankel, 1989). The basic concept of X-ray lithography (XRL) is proximity printing. The improvement of the aerial image using X-ray beams compared with 200 nm radiation is quite obvious with respect to Eq. (4-1).

Laser-based plasma sources (Chaker et al., 1991) emit "soft" X-rays of a wavelength (0.8–2.2 nm), which is short enough to give images not deteriorated by diffraction (Guo and Cerrina, 1991). Their medium brilliance (<10 mW/cm^2) requires highly sensitive resists (<50 mJ/cm^2), and their resolution capability (~0.2 μm) is controlled by the penumbral blur (Frackoviak et al., 1993). Such data are also achieved by deep ultra violet (DUV) lithography, and it is doubtful, whether this approach will see a breakthrough into large volume production. In contrast, bright (compact) synchrotron storage rings with a power of >100 mW/cm^2 are candidates to become production tools in the future for sub 0.2 μm

lithography (Yanof et al., 1992; Simon et al., 1998), due to their high resolution capability (>70 nm; Ogawa et al., 1993) combined with high throughput.

Other unique and important advantages of XRL are its insensitivity to dust particles and substrate topography (Yoshioka, 1990), as neither reflection nor backscattering effects occur, resulting in excellent linewidth control over topography as demonstrated in Fig. 4-8. Although these features make XRL superior to any other irradiation technique presently known, several problems exist, which have hampered its introduction into high-end IC production for more than a decade.

The large size of, and high capital investments for, synchrotron sources as well as their complex ancillary system are severe drawbacks in the competition with other technologies, but a cost per bit analysis demonstrates that synchrotron XRL might be the cheapest method of manufacturing ULSI-devices (Roltsch, 1991). Various functional circuits (e.g., SRAM with critical dimensions of 0.35 μm) have been manufactured using XRL (Technology News, 1993). The suitability of XRL for the fabrication of three-dimensional microelements for integrated optics, sensors, and microgears by the LIGA process (German: Lithographie, Galvanoformung, Abformung) will only be mentioned here (Rogner et al., 1992; Ehrfeld et al., 1998). The first 'commercialized' compact synchrotron with superconducting magnets is the high energy lithography illumination by Oxford's synchrotron (HELIOS) from Oxford Instruments (Kempson et al. 1991). Several state-of-the-art descriptions of synchrotron sources used in lithography have been given recently (Maldonado, 1991; Schmidt et al., 1991; Yoshihara, 1992; Cerrina, 1992; Smith, 1995).

The usable wavelength range of X-rays (0.5–4 nm) is determined by the absorption properties of the mask and of the resist.

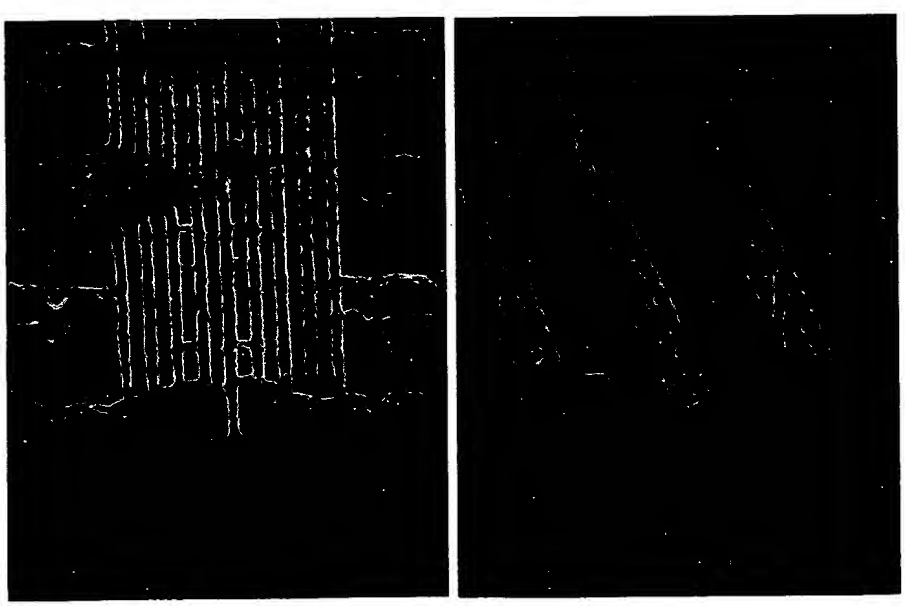

Figure 4-8. SEM photograph of AZR PN 114 (left: 0.4 mm lines & spaces; right 0.175 mm lines. Dose: 9 mJ/cm2, development: 60 sec. 0.135 N AZ™ MIF 312) over metal topography exposed with X-ray radiation provided by a laser plasma source. (Courtesy of Hampshire Instruments, Ltd. Reproduced with permission.)

These photons are neither r
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source. As no optical system
neither projection nor reduc
only 1:1 shadow printing
gaps of ~40 μm can be em
al., 1991). High quality X-
sist of a thin, X-ray transpa
(≤4 μm), which makes ther
to distortions due to absorbe
1991; Chaker et al., 1991). T
production and repair are
(Koek et al., 1993). These
not been satisfactorily solv
ten years. Recently, progre
ported (Wasik et al., 1998). I
curacy (<70 nm) has bee
(Tsuyuzaki et al., 1994;
1997).

4.2.3 Projection Printing

4.2.3.1 Near UV Projection

Current IC lithography
nated by projection printing
early 1980s, 1:1 full-field
projection cameras were th
IC lithography (Thompso
These machines operate wi
numerical aperture (NA) r
lens. Their benefits were h
and the property to allow
range of wavelengths. But
capability did not meet the
design rules. The increase
mirror lens gave way to cam
resolving power at the pena
posure fields, resulting in th
camera concept. Although
ras allow the *NA* to be doub
could not compete with the
reduction cameras (stepp
rently dominate advanced

These photons are neither reflected nor refracted by any material known today and have to be used as they are produced by the source. As no optical system can be applied, neither projection nor reduction techniques, only 1 : 1 shadow printing with proximity gaps of ~40 μm can be employed (Guo et al., 1991). High quality X-ray masks consist of a thin, X-ray transparent membrane (≤4 μm), which makes them very sensitive to distortions due to absorber stress (Acosta, 1991; Chaker et al., 1991). Their defect-free production and repair are difficult tasks (Koek et al., 1993). These problems have not been satisfactorily solved over the last ten years. Recently, progress has been reported (Wasik et al., 1998). High overlay accuracy (<70 nm) has been demonstrated (Tsuyuzaki et al., 1994; Aoyama et al., 1997).

4.2.3 Projection Printing

4.2.3.1 Near UV Projection Systems

Current IC lithography is clearly dominated by projection printing methods. In the early 1980s, 1 : 1 full-field scanning optical projection cameras were the workhorses of IC lithography (Thompson et al, 1983). These machines operate with a special, low numerical aperture (NA) ring-field mirror lens. Their benefits were high throughput, and the property to allow exposure over a range of wavelengths. But their resolution capability did not meet the aggravating IC design rules. The increase of the *NA* of the mirror lens gave way to cameras with higher resolving power at the penalty of smaller exposure fields, resulting in the step-and-scan camera concept. Although these new cameras allow the *NA* to be doubled (>0.3), they could not compete with the step-and-repeat reduction cameras (stepper), which currently dominate advanced IC production.

Modern steppers use monochromatic radiation (e.g. 436 nm or 365 nm, g- or i-line of the mercury emission spectrum, respectively; Fig. 4-7), a complex system of lenses with an *NA*>0.5 and allow diminution of the mask image by a factor of 5× or 10×. As the field dimensions of the imaging system are of limited size, only a small part of the wafer, i.e. a single chip, is exposed during one irradiation step (Fig. 4-9). This lowers the production throughput, but yields highly reproducible patterns, as the same mask is used for each distinct unit. Beside resolution and *DOF* (Yamanaka et al., 1993), the image field size is another important issue, as it decreases with increasing *NA* due to difficulties in manufacturing adequate optics of large size (Noelscher et al., 1990).

Several IC companies switched from g- to i-line lithography to manufacture the 4 MBit DRAM chips with critical dimensions (*CD*) of 0.8 μm, and now use this technology for the production of 16 MBit DRAMs or other devices with 0.5 μm design rules (Greeneich and Katz, 1990).

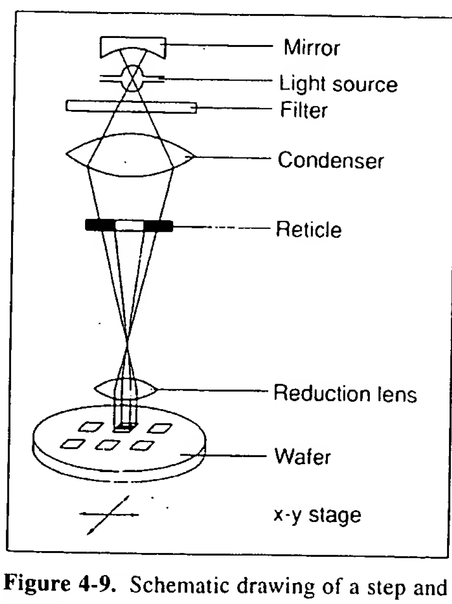

Figure 4-9. Schematic drawing of a step and repeat camera.

These products require a *DOF* budget of 1.5 µm due to topography, limited wafer flatness and focus error of the stepper (Peters, 1991). The first version of the 64 MB DRAM with *CD*s of 0.4 – 0.35 mm has been produced with i-line, but the shrunk versions (0.35 to 0.3 µm) required a switch to DUV lithography for certain critical levels.

4.2.3.2 Deep UV Projection Systems

As the production of small feature sizes is one major challenge in ULSI lithography, it became inevitable to investigate DUV radiation for providing higher resolution together with an increased *DOF* budget (Mack, 1993 a). However, previously used lens glass has to be replaced by quartz with high DUV transmission. Mercury-xenon lamps have a high radiation output in the near UV range, but a very low one in the 200 to 300 nm region, which excludes the use of narrow band pass filters to avoid chromatic aberrations and demands mirror projection optics. Two commercial DUV mirror projection systems operate with service-friendly and inexpensive high pressure mercury-xenon lamps. As their brilliance is poor, resists of high sensitivity (<5 mJ/cm^2) are mandatory. However, antireflective coatings may be omitted in the case of broadband illumination (Kuyel et al., 1991). The Ultratech stepper operates at a wavelength of 249 ± 3 nm, while the SVG Micrascan machine (step-and-scan concept) provides exposure illumination over a 240 to 255 nm bandwidth (Buckley and Karatzas, 1989).

A different approach to DUV illumination systems is based on excimer lasers (excited dimer), which are very powerful pulsed gas lasers, in which excited diatomic noble gas/halogen molecules formed by a high voltage electric discharge, e.g. XeCl (308 nm), and especially KrF (248.5 nm) or ArF (193 nm), emit the laser radiation during their transition to the repulsive ground state (Fig. 4-7; Jain, 1990). By injection locking, their emission is extremely narrow banded (<2 pm) and therefore no attention has to be given to chromatic aberration (Preil et al., 1991). Experimental resolutions of 0.15 µm have been reported using this technology (Hartney et al., 1992) and adequate alignment systems with an overlay accuracy <0.1 µm have been designed (Fig. 4-10; Wittekoek, 1992). Problems with respect to accurate dose control due to low reproducibility of pulse to pulse laser power have been resolved more recently (Kowaka et al., 1993). Excimer lasers can be integrated with reflective or refractive reduction optics to form useful images.

As indicated by the major exposure equipment manufacturers, projection systems for use in 193 nm lithography are currently on the verge of moving from R&D to production tools. It is evident that several basic requirements are still not met by the machines available today. Among the biggest challenges are the material selection for, and optimization of the lens system, as the high-energy radiation causes lens compaction and formation of color centers in al-

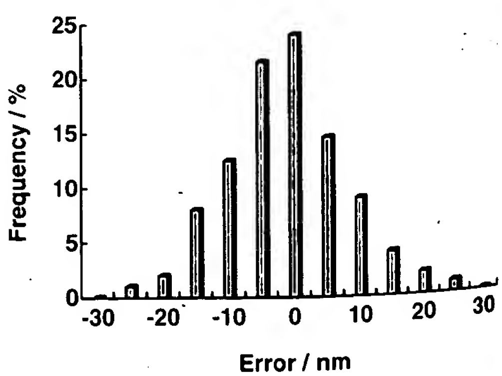

Figure 4-10. Overlay errors of an ASM-L DUV stepper. (Courtesy of ASM-Lithography. Reproduced after Wittekoek, 1992.)

most all suitable materials (Schenker et al., 1996).

The potential and future of optical lithography, including sub-half-micrometer resolution, has been discussed in detail from various more specialized aspects recently (Arden, 1990 and Yamanaka et al., 1993). The supply of irradiation equipment for device fabrication, in general steppers, is presently dominated by six companies: Nikon, Canon, Hitachi (all Japan), Ultratech, Integrated Solutions (U.S.A.), and ASM-Lithography (Netherlands). Step-and-scan machines are available from SVG Lithography (U.S.A.) (Cromer, 1993) and ASM-Lithography, Nikon and Canon also started to offer scanners. More recently, Japan-based Komatsu announced its intention to produce and market lithography exposure tools.

4.2.3.3 *Nonconventional UV Lithography*

An extension of optical projection lithography is expected from the use of optical tricks, like the phase-shifting mask technology (PSMT; Levenson, 1992), the off-axis illumination technique (Shiraishi et al., 1992), the optical proximity correction (OPC) (Levenson, 1997), the focus latitude enhancement exposure (FLEX; Fukuda et al., 1991), or the outline pattern transfer imaging (OPTIMA; Tanaka et al., 1991 b), pupil filtering (Fukuda et al., 1994) (all developed to practical performance by groups at Hitachi), holography (Omar et al., 1991), imaging interferometric lithography (Brueck, 1998) and phase contrast lithography (Mack, 1993b). Certain restrictions with respect to mask making and pattern geometry limit their general applicability.

Levenson (1992) concluded from calculations that g-line PSMT would resolve sub 0.5 mm patterns. Later Terasawa et al. (1989) presented 0.3 µm wide periodical gratings using a low *NA* i-line stepper. Today i-line PSMT is feasible for sub 0.3 µm printing (Shirai et al., 1991; Watson et al., 1997), which favors it as a major competitor to DUV lithography for 64 MBit memory fabrication. Several IC giants with their own well-developed mask shops have selected i-line PSMT as their first candidate for printing 0.35 µm. PSMT is usable for all variants of photonic radiation, including excimer laser lithography (Sewell, 1991). It takes advantage of interference to omit certain diffraction effects typical for light projected through small apertures, which results in an improved aerial image (Fig. 4-11).

Light, as an electromagnetic wave, has a phase and an amplitude. A conventional mask (Fig. 4-11a) consists of a quartz plate imagewise covered with an opaque layer, which defines the apertures of the patterns. Constructive interference between periodic openings enhances both the electric field and the light intensity to a maximum between them, thus reducing contrast and resolution. In the Levenson-type PSMT (Fig. 4-11 b) bordering apertures are covered with a transparent phase shifting layer, which reverses the sign of the electric field with the effect that bordering waves are 180° out of phase with one another. At the wafer plane destructive interference occurs, which minimizes the undesired light intensity between two adjacent openings (Levenson, 1992).

Using simple pattern geometries, k_1 factors of <0.35 have been demonstrated under laboratory conditions, resulting in minimum patterns of 0.24 µm and 0.16 µm for i-line and DUV irradiation, respectively (Ohtsuka et al., 1991; Baik et al., 1993; Matsuoka and Misaka, 1997). The Levenson-type mask layout offers the greatest increase in resolution and *DOF*; however, it is limited to periodic grating patterns (Brock et al., 1991), because of its termination problem: phase shifts in the middle of clear ar-

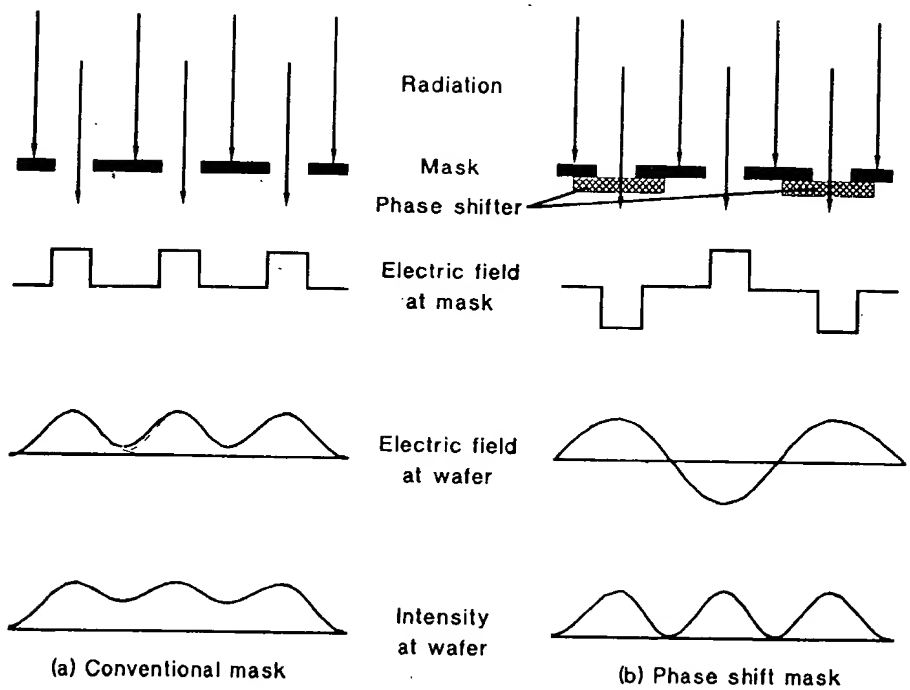

Figure 4-11. The change of aerial image intensity by applying Levenson-type PSM-technology: use of (a) a conventional and (b) a phase shift mask.

eas of the mask produce artefacts on the device, when positive tone resists are used (Jinbo et al., 1990). During the last years, many alternative mask configurations, which can be used for printing of isolated patterns have been discussed (Toh et al., 1991a; Yanagishita et al., 1991; Levenson et al., 1992; Ronse et al., 1993). An overview of the important PSM technology variants is given in Fig. 4-12. To get highly precise masks is difficult due to possible errors in phase and transparency. Pupil filtering is proposed to relax the mask error tolerances (Nakao et al., 1997), because a strict control in mask structure is required to obtain *CD* control. The main PSM suppliers, namely Dai Nippon Printing, Hoya and Toppan, have started sampling masks.

Currently off-axis illumination has become very popular as a resolution enhancement technique. However, pattern deformation phenomena may occur mainly in island type patterns (Kim et al., 1997). Line width deviations caused by lithography or etch effects can result from local pattern density variations (Fujimoto et al., 1997). OPC is a low cost technique to reduce such problems (Liebmann et al., 1997). The FLEX method is used for printing of isolated transparent patterns, like contact holes, using positive resists (Fukuda et al., 1991), while the OPTIMA approach was applied to 0.2 mm regular patterns with practical focus (> 1.0 μm) latitudes and 0.13 μm-wide groove patterns using a 0.5 μm thick negative-tone i-line resist (Tanaka et al.; 1991b). The off-axis illumination techniques are favoured by the exposure equipment suppliers, as only minor modifications in the optical path are required. Canon and Nikon offer units called CQUEST (Canon quadrupole efficient stepper technology) and SHRINC (super high

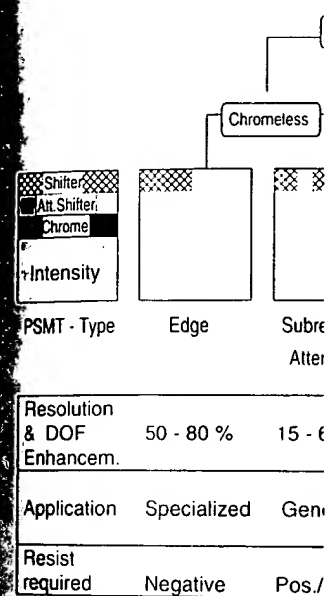

Figure 4-12. Overview of variou

resolution by illumination c
tively, for their existing g-
DUV steppers, and have
DOF enhancements (Shirai
The advantage of this appro
to the patterning of peri
(Partlo et al., 1993). Imagin
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raphy should be extende
$CD \sim \lambda/3$, which means 12
(Brueck, 1998). A holograph
an effective *NA* of 0.7 has be
by Clube et al. (1993) from
nologies for printing 0.25 μ
a 0.5 μm thick i-line resist. T
proximity printer achieves
resolution over a very large
improvement of the presen
bility of ±0.5 μm is currentl

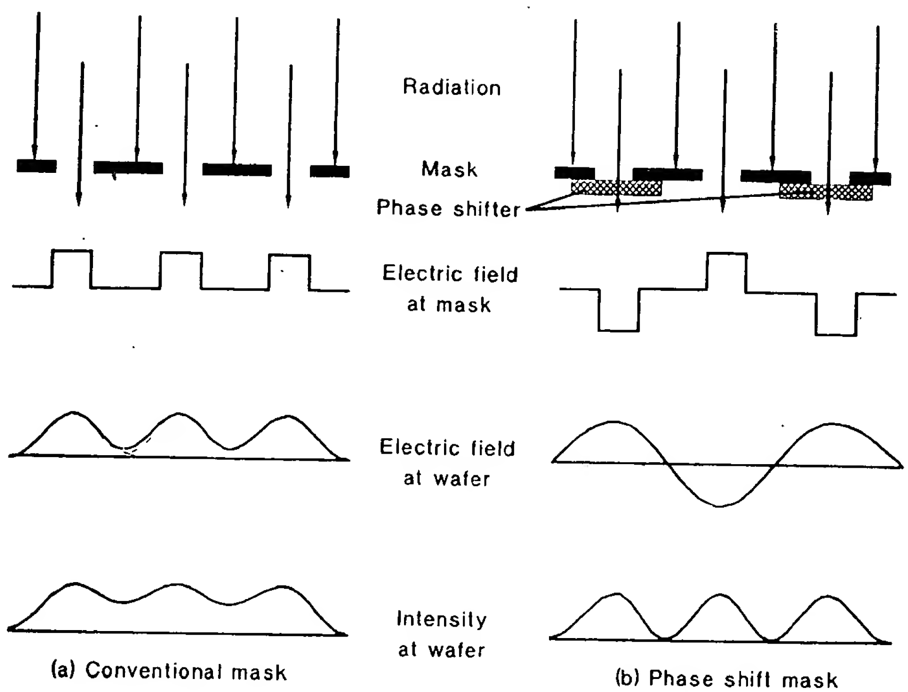

Figure 4-11. The change of aerial image intensity by applying Levenson-type PSM-technology: use of (a) a conventional and (b) a phase shift mask.

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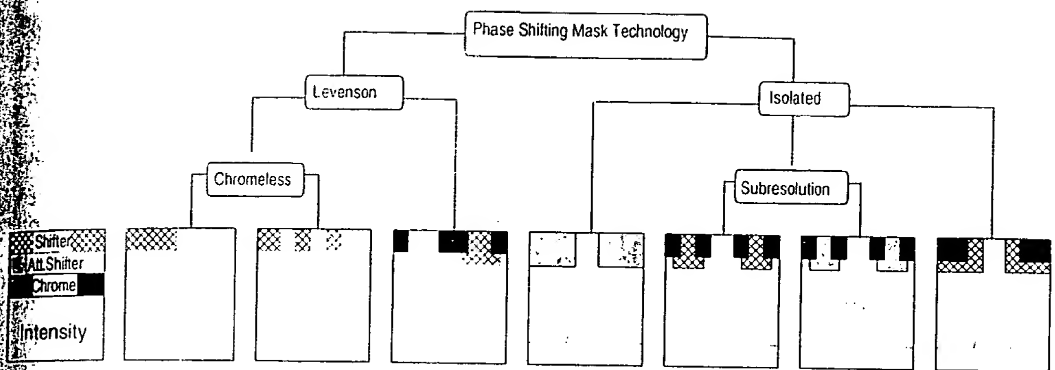

PSMT - Type	Edge	Subresolution Attenuation	Alternating	Chromeless Attenuation	Non Attenuated	Attenuated	Rim
Resolution & DOF Enhancem.	50 - 80 %	15 - 60 %	40 - 60 %	15 - 25 %	15 - 25 %	15 - 25 %	10 - 20 %
Application	Specialized	General	Packed patterns	General	Contacts	Contacts	General
Resist required	Negative	Pos./ neg.	Negative	Positive	Positive	Positive	Positive

Figure 4-12. Overview of various phase shifting mask technologies. (Reproduced from Buck et al., 1991.)

resolution by illumination control), respectively, for their existing g-line, i-line and DUV steppers, and have reported 100% *DOF* enhancements (Shiraishi et al., 1992). The advantage of this approach is restricted to the patterning of periodic structures (Partlo et al., 1993). Imaging interferometric lithography combines off-axis illumination with interferometric optics. Modeling results show that the limits of optical lithography should be extended to roughly $CD \sim \lambda/3$, which means 120 nm for i-line (Brueck, 1998). A holographic method with an effective *NA* of 0.7 has been investigated by Clube et al. (1993) from Holtronic Technologies for printing 0.25 μm features into a 0.5 μm thick i-line resist. The holographic proximity printer achieves a high imaging resolution over a very large field size. The improvement of the present overlay capability of ±0.5 μm is currently under study.

4.2.4 Post-Optical Lithography

The requirements of optics and materials are becoming increasingly crucial for even smaller patterns, such that optical lithography seems to be approaching its technological limit. Therefore, nonoptical lithographies such as electron beam, X-ray, and ion lithographies are increasingly important in order to replace or mix and match with optical lithography. It should be noted that post-optical lithography requires not only higher resolution capability but also more accurate controllability in terms of mask and overlay than conventional optical lithography. High throughput rate is also required (Ishitani, 1998).

Direct Writing

Electron beam lithography (EBL) currently dominates the photomask manufacturing industry (Pfeiffer and Groves, 1991).

and has a strong position as patterning method for prototype devices and advanced application specific integrated circuits (ASICs) or very high speed integrated circuits (VHSI), which are produced in small quantities (Newman et al, 1992). EBL is a pivotal element in microlithography and has largely contributed to progress in miniaturization (Pethrick, 1991). Currently used e-beam machines have been developed from the electron microscope. The beam is deflected and shaped by a series of electrostatic and magnetic optics. Direct writing ("scanning") e-beam lithography employs either a round gaussian or a rectangular (fixed or variable) shaped beam suitable for building high resolution devices or providing high throughputs, respectively. Gaussian e-beam tools work in two scan versions: in the raster mode the beam scans the entire wafer along a serpentine path and is "switched" on and off, whereas in the vector mode it is directly addressed to its pattern position resulting in a considerable throughput enhancement (e.g. Philips Beamwriter). The shaped beam tools normally work in the vector scan mode.

EBL is characterized by an extremely high resolution capability (40 nm; Classen et al., 1992), but electron scattering through the resist material and more intensively through the substrate limit practical resolutions to >100 nm (proximity effect), especially when thick resist layers are employed. Software for proximity correction has been developed, e.g. CAPROX (Knapek et al., 1991). Figure 4-13 shows a simulation of the electron scattering at 10 keV, and 20 keV acceleration voltage. Obviously, the scattering range increases drastically with increasing energy, while the beam expansion in the resist is significantly reduced resulting in higher resolution (Rosenfield et al., 1991). Unfortunately, this is accompanied by a higher defect density in the substrate, caused by electron bombardment (Pethrick, 1991). High resist sensitivity helps to reduce these defects.

Direct write e-beam lithography is highly flexible because it obviates the use of a mask. The main drawbacks are the low throughput due to serial writing, and the relatively large investment costs making the manufacture of ICs via e-beam equipment only competitive with mask replication methods, if a number of less than 50 wafers is considered. Suggestions have been made concerning raising the wafer throughput by means of an array of microcolumns, based on the scanning tunneling microscope aligned field emission (SAFE) concept (Chang et al., 1992). Throughput of 50 wafers per hour for 100 nm lithography may be achievable, depending on the number of col-

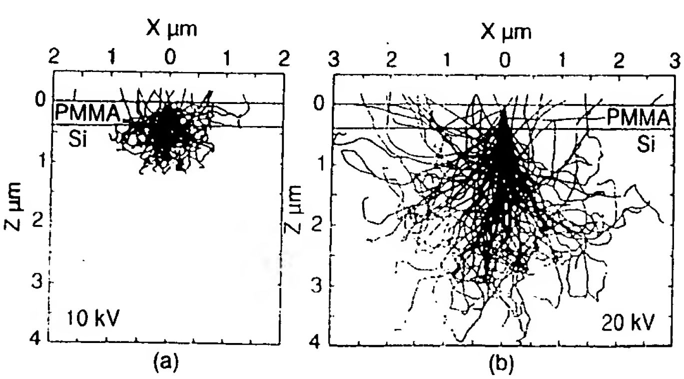

Figure 4-13. Monte Carlo simulated trajectories of 100 (a) 10 keV, (b) 20 keV electrons in a 0.4 mm poly(methyl methacrylate) resist layer on silicon. (Reproduced after Kyser et al., 1975.)

umns employed. The e›
of a scanning tunnelling
microscope (STM, AFM
low energy electrons (≤
normal atmospheric pre
used to pattern very thin
ning nearfield lithogra
niques offer a cheap wa
of sub-100 nm patterns b
is extremely low (Marria
and Campbell, 1994).

More recently, optica
systems as provided b
HeCd (442 nm) or Ar$^+$ (
proven their competitiv
based processes by del
structures under manuf
(Rensch et al., 1989). T
and ASIC patterns may
of this exposure variant.
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Ion beam lithograph
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Robinson, 1989; Morga
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Electron and Ion Proje

Electrostatic lenses a
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